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PROPELLER NOZZLES DESIGN USING VISCOUS CODES AND OPTIMIZATION ALGORITHMS

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Abstract. Marine propellers design requirements are always more pressing and the application of unusual propulsive configurations, like ducted propellers with decelerating nozzles, may represent a valuable alternative to fulfil stringent design constraints. If accelerating duct configurations were realized mainly to increase the propeller efficiency in highly-loaded conditions, decelerating nozzles sustains the postponing of the cavitating phenomena that reflects into reduction of vibrations and radiated noise. The design of decelerating nozzle, unfortunately, is still challenging. No extensive systematic series are available and the design relies on few measurements. On the other hand, viscous flow solvers appear as reliable and accurate tools for the prediction of complex flow fields. Hence, in the present paper the opportunity to use CFD as a part of a design procedure based on optimization, by combining a parametric description of the geometry, the OpenFOAM solver and a genetic type algorithm in the ModeFrontier environment, is investigated. Design improvements for both accelerating and decelerating ducts are measured by comparing the performance of the optimized geometries with those of conventional shapes available in literature.

1 INTRODUCTION

Marine propellers design requirements are, nowadays, always more pressing. Not only maximum efficiency, but also comfort and environmental demands and regulations have to be satisfied. The application of unusual propulsive configurations may represent a valuable alternative to fulfil these constraints. Contra-rotating and tip loaded blades (CLT and Kappel like geometries) were used to improve propulsive efficiency, together with Energy Saving Devices, like pre- and post- swirl stators, PBCF or Mewis Ducts. Combinations of these devices mounted on PODs (i.e. through the EU project TRIPOD, [1]) were exploited to maximize the effects and to provide flexible propulsive systems able also to reduce side effects like induced pressure pulses and vibrations by operating the propellers in more uniform inflow, with minimum optimal diameters and far from the hull. Ducted propellers represent an additional, valid, answer to current design requirements.

In the case of vessels for which requirement of high thrust are critical in the low speed operation range, or when the screw is limited in diameter, the use of accelerating nozzles is widely documented in literature: with accelerating nozzles, the duct increases the flow rate through the propeller, which consequently operates at a more favourable loading. The nozzle by itself produces a certain positive thrust.

This conceptual idea dates back to Stipa [2] and Kort [2] but probably the works by Van Manen [4], Van Manen and Superina [5] and Van Manen and Oosterveld [6] represent some of the most accurate reviews of ducted propellers performance and design guidelines. By combining even simple theoretical considerations and systematic measurements, they provided a rather wide overview of the influence of some geometrical parameters of nozzles on efficiency, correlating non-dimensional parameters and performance in case of both highly- and lightly- loaded propellers. They identified the nozzle profile number 19A as the optimal compromise, having performance in towing and pushing conditions not appreciably inferior to those of considerably longer nozzles. This shape, fifty years later, is still the default choice in the case of accelerating ducted propellers applied to a variety of boats and vessels (tugboats, towboats, and supply vessels) which require increased propulsive efficiency especially near the bollard pull condition.

In the same works, also the potentialities of flow decelerating type of nozzle were pointed out. By reducing the flow rate to the impeller, a local increase of the static pressure is achieved, which could be effective in retardation of propeller cavitation phenomena at a cost, unfortunately, of efficiency reduction and an additional drag represented by the negative thrust delivered by the duct itself. An improvement of the cavitation characteristics of the propeller can be obtained, thus, only if the gain in static pressure exceeds the unfavourable effect of the increased screw loading, necessary to compensate the duct drag. In addition, the risk of duct cavitation (at leading edge or midchord, depending on the propeller loading and the camber of the nozzle) represents another issue to account for in evaluating the usefulness of the decelerating configuration.

The design of decelerating nozzles, which consequently seem to better comply with the constraints circa radiated noise and vibrations strictly related to cavitation suppression, is however still challenging and poorly addressed in literature. Despite the wide employment of this propeller configuration (i.e. fast carriers and navy vessels for which side effects reduction is significantly more important than propulsive efficiency), there are several design and analysis issues still open. No systematic series, widely diffused in the case of accelerating configurations, are available and the design still relies on few measurements and data. From a theoretical/numerical point of view, the availability of literature data is even scarce. Apart classical momentum theories [6] applied to decelerating duct geometries, only few applications are available. Abdel Maksoud et al. [7] developed a design and analysis method for multi-component propulsors. Gaggero et al. [8] developed a design approach based on optimization through Boundary Elements Methods. Results, confirmed by dedicated RANSE calculations and model scale measurements, concerned however only the well-established problem of propeller blades design, using given nozzle shapes. The inclusion of the duct shape in the optimization process, certainly possible, would have excessively stressed, over the inherent limitations of the potential approach, the applicability of BEM to predict nozzle forces, significantly influenced by viscous effects and flow separation with the risk of obtaining shapes conditioned by the low fidelity level of the computational tool. Recently, yet in the framework of potential flow based theories, some analyses of decelerating duct shapes with momentum theory and semi-analytical actuator disk models to account for radial distributions of forces have been proposed [9]. All these calculations, however, neglect the influence of viscosity which instead, also in the simpler case of accelerating nozzles [8,10,11] significantly influence duct and propeller forces by interacting with the flow at the duct/propeller tip gap giving rise to typical tip leakage vortexes.

As the consequence of the need of a reliable and efficient design tool for accelerating and decelerating propeller nozzles, in the present work optimization is exploited to investigate the possible enhancement of nozzles performance provided by the application of high-fidelity numerical tools embedded into an automatic process. Thousands of different geometries, defined by a parametric description, need to be tested and verified against appropriate design criteria (specifically derived for both accelerating and decelerating configurations) to define an optimal geometry that, due to the multi-objective nature of design, is of course a balance of contrasting purposes. Only thanks to the favourable ratio between accuracy and computational efficiency of simplified representations of the influence of the propeller on the nozzle performance, such the ones represented by actuator disks, the process is possible in a reasonable computational time compatible with the usual design routine. After a validation based on the measurements carried out at the cavitation tunnel of the University of Genoa, actuator disk models, already proposed with success for the analysis of accelerating ducts performance, will be therefore employed also for the analysis of decelerating ducts and, through optimization, for the improvement of the performance of reference nozzle geometries.

2 NUMERICAL METHODS

2.1 Flow solver and computational domain

Detailed analyses of duct performance cannot be achieved by simply using inviscid flow models. Flow separation, except by using heavily approximated formulations, is beyond potential flow calculations and blunt trailing edges, in the particular case of accelerating ducts, pose significant difficulties for the application of the Kutta condition. Viscous models are definitely needed and RANSE approximations with suitable turbulence models can adequately answer all the specific issues related to design procedures.

In this study, OpenFOAM [12] has been employed. OpenFOAM is a collection of libraries suited for the solution of partial differential equations using a Finite Volume approach and cell-centered collocated variables with face-based implementation to allow for arbitrary cell shapes. Pre-processing, solvers and post-processing tools are fully scriptable, which is of fundamental importance when a completely automatic process has to be setup. For this particular application, where steady flow with respect to a blade fixed reference frame is expected, the *simpleFOAM* solver with the *SST k-ω* turbulence model has been used: continuity and RANSE equations are solved in a segregated form, with a SIMPLE based pressure-velocity correction and under-relaxation to achieve steady state solutions. Second order accurate schemes in space have been preferred for momentum and turbulence equations.

The axisymmetric nature of the flow allows the use of “smaller” computational domains that, without the effective presence of the propeller blades substituted by distributions of the momentum sources of the actuator disk, could be reduced to a sector narrower than a blade passage. The simplest formulation available in OpenFOAM exploits “wedge type” boundary conditions for purely axisymmetric calculations. For 2 dimensional axisymmetric cases, the geometry is specified as a wedge of small angle (<5°) and 1 cell thick running along the plane of symmetry, straddling one of the coordinate planes, as shown in Figure 1. With this arrangement, only momentum sources in the axial directions are allowed and all the flow features different from those on the meridian plane (i.e. slipstream rotation) are neglected. Slipstream flow has a certain importance [10], especially in correspondence to highly loaded functioning. In present case, the need of computationally efficient calculations and the "comparative" nature of the design by optimization encourage the use of the efficient setup consisting in the two-dimensional wedge formulation, thus neglecting the three-dimensional nature of the flow accounted, instead, with three-dimensional calculations and cyclic boundary conditions.

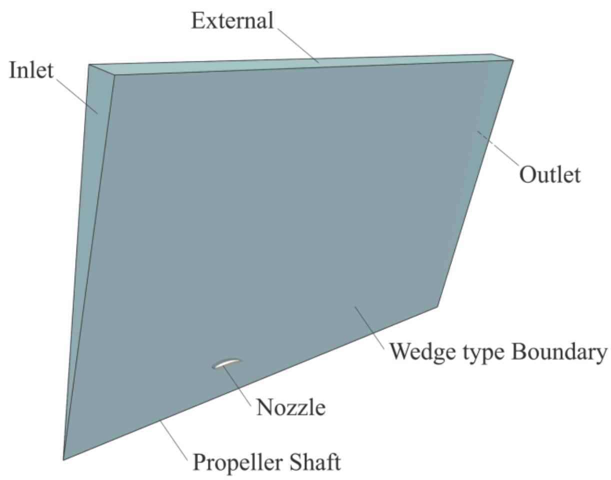


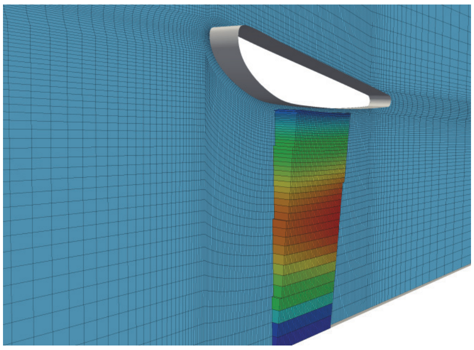
Figure 1: Computational domain with "wedge type" boundary conditions for the analysis of ducted propeller performance.

Also the propeller hub, in the shape of an infinitely long shaft, has been included in calculations. Its presence has a certain positive influence on the thrust delivered by the duct: momentum sources are distributed over a small area, inducing higher velocities that change the angle of attack of the nozzle and the resulting pressure distribution. Details of the hub shape would be also important. In present calculations, focused more on the definition of a procedure for nozzle shape design rather than on the exact characterization of the flow, the simplest adoption of an infinitely long shaft with a slip boundary condition was deemed sufficient to account at least for its principal influence. The final computational domain consists in an angular sector with the inlet placed 2 propeller diameters in front of the nozzle and the outlet 5 propeller diameter aft the nozzle. The external boundary lies on a cylindrical surface 4 propeller diameter from the propeller shaft.

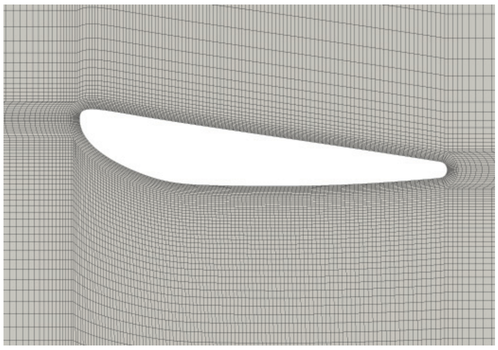
2.2 Propeller model and grid arrangement

The influence of the propeller on the flow around nozzles has been modelled by using an actuator disk. The actuator disk can be seen, definitely, as an infinite bladed propeller. The load of the propeller is distributed over the entire area of the propeller, neglecting the real material nature of a finite number of blades. Even if more detailed representation of blade forces are available [13], by using local momentum sources, their application for the characterization of flow in the nozzle design process seems redundant. Only the radial distribution of load can be considered important, influencing the risk of flow. In present calculations, the radial distributions of forces have been derived from Boundary Elements Method analyses and loaded into RANSE by using interpolating tables and polynomials through a dedicated library specifically developed to extend the computational functionalities of OpenFOAM.

In the light of dealing with flow separation, calculations have been carried out with a sort of "GAP" model, similar to that proposed in the case of BEM calculations and applied in the case of simplified viscous calculations [13] to easily account for the influence on loading of phenomena like tip leakage vortices. The proposed actuator disk is a finite thickness disk of width equal to the average thickness "cut out" by the propeller (Figure 2). Grids were arranged accordingly to the computational domain selected for the analyses by using the OpenFOAM *blockMesh* utility. A structured multi-block layout has been preferred to describe in details the most important features of the nozzles, to ease and to speed the automatic generation of the mesh possible thanks to the scriptable nature of the utility and necessary for optimization purposes. In the case of accelerating duct configuration, essentially an O-grid mesh has been setup to have better resolution at the blunt trailing edge. C-type grids were adopted, instead, in the case of decelerating geometries to manage the sharp trailing edge of the nozzle. The final arrangement consists in a one cell thick layer of 17600 structured hexahedral elements, setup around surfaces with appropriate grading to comply with wall treatment modelling through wall functions. An example is shown in Figure 2.



(a) Actuator disk representation.



(b) Multi-block structured mesh.

Figure 2: Actuator disk representation into the computational domain (a) and computational mesh (b) for the accelerating nozzle. Colours represent the strength of the momentum sources per unit volume.

2.3 Parametric description of nozzles

The parametric description of nozzles is rather simple, since nozzles are definitely hydrofoils that could be handled, analogously to what already done in the case of propellers [14] and wings [15], by using B-Spline curves for both camber and thickness distributions. In present calculations, however, a slightly different approach has been adopted. In order to avoid unfeasible shapes (i.e. maintain the inner duct surface on a cylindrical surface of a given radius) it was preferred to describe with B-Spline curves directly the inner and the outer contour of the nozzle to facilitate the application of the geometrical constraints [16].

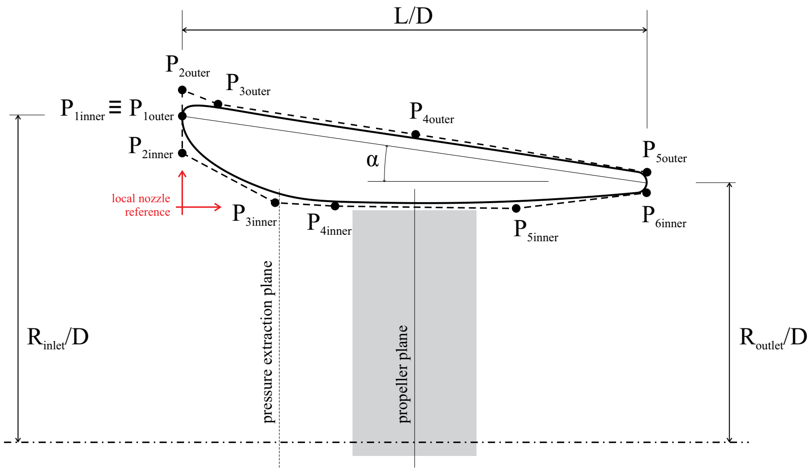
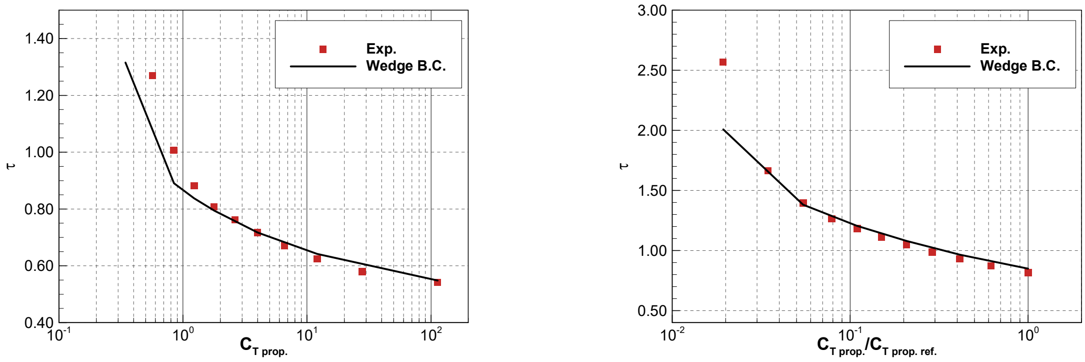


Figure 3: Parametric description of nozzles shape. Accelerating duct case.

The B-Spline curves control points, as shown in Figure 3, are free to move with some "compatibility" constraints at leading and trailing edges. Furthermore, the control points that handle the central part of the inner surface have to be altered only axially to keep the nozzle shape rectilinear at propeller location. With these assumptions, the description of the accelerating duct consists in 11 free parameters while the decelerating nozzle has 7 degrees of freedom. In both cases, a scaling factor in the axial direction is added to change anysotropically the length/diameter ratio. Choices, also on the basis of previous experiences, are motivated by the need of a trade-offs between allowed modifications (the widest possible) and fairness of the geometry that is facilitated, in any case, by the use of B-Spline curves.

3 VALIDATION OF THE SIMPLIFIED MODEL

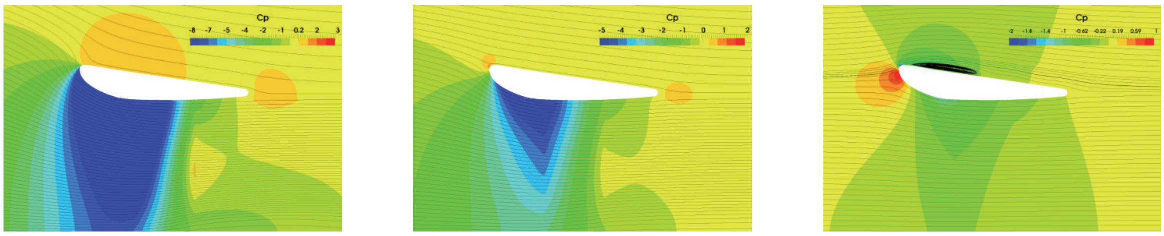
The validation of the computational tools has been carried out considering two ducted propellers for which measurements of forces and flow are available [8]. The first one is an accelerating duct propeller with a usual Nozzle 19A, designed for a take home propulsor. The second one is a decelerating duct propeller developed to postpone cavitation for applications in which reduction (or better, retardation) of noise is important, such as navy ones. In both cases, differently from usual Kaplan like geometries, propellers are unloaded at tip and have a small chord, which made the selection of the optimal nozzle shape problematic. By using a Boundary Elements Method, the radial distributions of axial force on the propeller blades were derived and momentum sources were assigned over the actuator disks coherently. Predicted forces exerted by the nozzles were compared to those measured during experiments. Results are shown in Figure 4. As usual thrust coefficients of propeller and nozzle ($C_{T\ prop}$ and $C_{T\ Nozzle}$ made non-dimensional with respect to the inflow velocity V and the area of the propeller disk) are compared in terms of thrust ratio τ in order to verify that the relative contribution of the duct to the total thrust increases with increasing propeller loading. Results, for both the nozzle geometries, are in good accordance with experimental data. Calculations well reproduce the experimental observations and from medium to heavy loading conditions, the agreement between calculations and measurements is good. The inclusion of the tangential forces as an additional momentum source distribution could have a favorable effect on the numerical calculations.



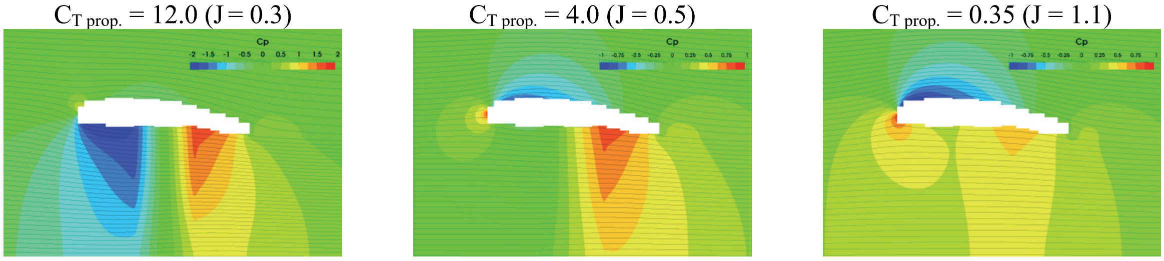
(a) Accelerating Duct. (b) Decelerating Duct.

Figure 4: Comparison of measured and computed nozzle thrust. Decelerating duct. For confidentiality reasons, decelerating duct values are given non-dimensional with respect to a reference functioning condition.

As pointed out in Hoekstra (2006), the additional pressure drop in the swirling slipstream due to the modelling of tangential velocities increases the pressure difference between the inner and the outer duct surface, raising the duct forces to values closer to measurements [17]. Especially in the case of the accelerating duct geometry, the thrust of the nozzle is significantly overestimated in lightly loaded conditions.



$C_{T\ prop.}$ = 12.0 (J = 0.3) $C_{T\ prop.}$ = 4.0 (J = 0.5) $C_{T\ prop.}$ = 0.35 (J = 1.1)



$C_{T\ prop.}/C_{T\ ref.}$ = 0.41 (J = 60% $J_{ref.}$) $C_{T\ prop.}/C_{T\ ref.}$ = 0.11 (J = 100% $J_{ref.}$) $C_{T\ prop.}/C_{T\ ref.}$ = 0.02 (J = 140% $J_{ref.}$)

Figure 5: Streamlines and inner pressure distribution at different loading conditions. Accelerating and decelerating ducts. For confidentiality reasons, the reference decelerating nozzle shape cannot be disclosed.

This difference may be explained by considering that the flow predicted by the actuator disk models is axisymmetric and neglects the tip leakage vortex, which can alter the streamlines path in circumferential direction and produce a negative interaction with the duct blunt trailing edge [13]. Streamline patterns and inner pressure fields for the two nozzle geometries are shown in Figure 5. The position of the leading edge stagnation point is evident, as well as how streamlines change with propeller loading. Streamlines approach Nozzle 19A almost along its camber line for a propeller thrust coefficient $C_{T\ prop.}$ of about 4 while in lightly loaded conditions the risk of a separation bubble on the outer side is clear, completely in agreement with the design of the nozzle, devoted to highly loaded functioning. For the decelerating nozzle shape, it is possible to appreciate the increase of the inner pressure close to the design point ($C_{T\ prop.}$ / $C_{T\ prop.\ ref.}$ = 0.10, J = 103.4% of $J_{ref.}$), together with streamlines approaching the nozzle at its ideal angle of attack.

3 OPTIMIZATION OF NOZZLES

The design of nozzles through optimization was achieved starting from two reference geometries available at the cavitation tunnel of the University of Genoa. In both cases, the design consists in the analysis of an initial population, selected by using the quasi-random Sobol sequencing, of 150 members, whose distribution in the design space supplies a sufficiently uniform description of the possible geometrical combinations. The optimization workflow, built in the ModeFrontier [18] environment, lets the initial population evolve for 15 generations that, in the light of preliminary calculations and the relative low number of free parameters, were considered sufficient to achieve convergence. The need to handle opposite objectives requires the use of multi-objective optimization algorithms that, in present calculations, are of genetic type. For an accelerating nozzle, which is usually designed to operate close to bollard pull, the maximization of the duct thrust at a given propeller loading conflicts with the need of reasonably high values of inner static pressure to contrast cavitation inception. For a decelerating duct propeller operating at relatively high advance coefficients, maximization of the static pressure at the minimum cost of increased duct drag turns into the design objective, to be achieved, in very critical functioning conditions, avoiding the risk of cavitation on the outer surface of the nozzle.

Avoiding local minima was considered important for the analysis of trends and of the influence of combinations of parameters. Genetic algorithms, with the inclusion of a certain randomness in the selection of the characters of any subsequent generations, allow more unrestrained analyses and a certain margin against local minima. A real design would require accounting for the interactions taking place between the duct and the propeller to exploit the maximum from both the designs. The use of actuator disk models (as proposed in this work) does not permit any type of interactions on propeller forces being these ones prescribed and independent of the force on the nozzle. Only by a blade redesign, it would be possible to have a sort of feedback and to design a propulsive system for a given total thrust. By assuming an unchanged propeller thrust (i.e. actuator disk intensity), instead, the analysis of the optimal geometries has to be restricted to those nozzle shapes that delivering the thrust of the reference geometry (i.e. not changing the functioning condition), improve performance in terms of inner static pressure. Any other case has to be regarded as the first step towards the redesign of propellers blade that of course will take advantage of the unloading provided by the higher thrust delivered by the newly designed duct.

3.1 Accelerating ducts

The outcomes of the design by optimization of the accelerating duct are summarized in the Pareto diagram of Figure 6. Among the design activities taken into consideration, the one involving the accelerating duct is the more complex. It considers, indeed, multiple functioning conditions. The nozzle is designed to provide the maximum thrust close to bollard pull condition that in numerical calculations was approximated with the functioning at a relatively low propeller advance coefficient ($C_{T\ prop.}$ = 12, $J_{prop.}$ = 0.3) to avoid the complications related to zero inflow. At the same time minimization of the nozzle drag at higher advance coefficients ($C_{T\ prop.}$ = 1.23, $J_{prop.}$ = 0.8) was required, together with maximization of inner static pressure (average pressure on a propeller disc in front of the actuator disc at x/D = -0.15 as in Figure 3) at both functioning. Results of the optimization process show certain margins of improvements, which can be verified by considering some relevant geometries among those belonging to the Pareto Frontier.

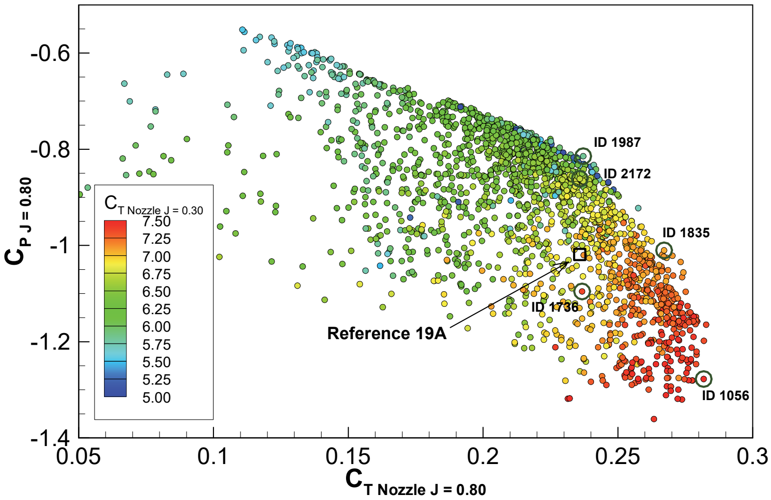
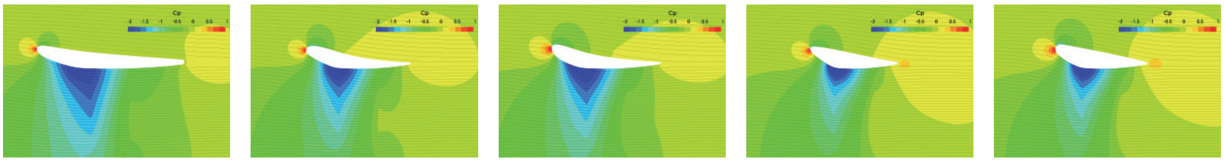


Figure 6: Pareto diagram of the accelerating duct design by optimization. Correlation between nozzle thrust and average inner pressure at the higher advance coefficient (J = 0.80, $C_{T\ prop}$ = 1.23).

As outlined in the discussion, without redesigning the propeller, the recommended optimal nozzles are those operating at constant thrust coefficient in order not to change the functioning point of the propulsion system. Depending on the importance of bollard pull with respect to routinely operative conditions at higher advance coefficient, there are multiple possible choices. In present design, where the reference propeller/nozzle system was designed for take home purposes (i.e. provide a reasonably high thrust with a small propeller at a relatively high advance coefficient), it was considered mandatory, at first, to improve the performance at the higher advance coefficient. In order to limit cavitation phenomena, moreover, the increase of the inner nozzle pressure in this condition is another important objective of the design that turns into the second most important aspect for the selection of an optimal geometry. Among the Pareto geometries, ID 2172 is the optimal balance between the opposite design requirements. Providing a constant thrust at the higher advance coefficient ID 2172 increases, at that condition, the inner static pressure at its maximum without worsening the performance at bollard pull (constant thrust) in correspondence to which a certain improvement in terms inner pressure can be appreciated too. Other geometries presuppose trade-offs among objectives. At constant nozzle delivered thrust for J = 0.80, ID 1987 provides the maximum increase of static pressure (appreciable also at bollard pull) at the cost of a sensible reduction of bollard pull thrust. On the opposite, ID 1736 maximizes bollard pull performance at constant thrust for J = 0.80 with a detrimental influence on cavitation avoidance. By accepting the redesign of the propeller, ID 1835 exploits the maximum thrust from the propeller without any significant influence on pressure fields while ID 1056 is devoted only to the maximization of nozzle delivered thrust regardless the inner pressure field. Detailed descriptions of the geometrical modifications necessary for these achievements are summarized in Table 1 while in Figure 7 the computed pressure and velocity fields are shown for the selected geometries.

Table 1: Performance of the selected designs for the accelerating duct case.

	Nozzle 19A	ID 2172	ID 1987	ID 1736	ID 1835	ID 1056
$C_{T\,Nozzle}$ ($J = 0.3$, $C_{T\,prop.} = 12$)	6.731	6.725	5.829	7.370	7.080	7.510
$C_{T\,Nozzle}$ ($J = 0.8$, $C_{T\,prop.} = 1.23$)	0.238	0.236	0.237	0.237	0.267	0.282
C_P ($J = 0.3$, $x/D = -0.15$)	-9.363	-8.368	-7.268	-9.866	-9.239	-11.105
C_P ($J = 0.8$, $x/D = -0.15$)	-1.019	-0.861	-0.815	-1.096	-1.010	-1.278



ID 1056 ID 1835 ID 1736 ID 1987 ID 2172

Figure 7: Streamlines and inner pressure distribution for the selected optimal geometries. Accelerating nozzle at higher advance coefficient condition ($J = 0.8$, $C_{T\,prop.} = 1.23$).

3.1 Decelerating ducts

The design of the decelerating nozzles has been carried out considering, in addition to the reference propeller load, two further conditions characterized by the same radial force distribution but total load respectively increased (+20%) and decreased (-20%). Aim of the analyses is to show the sensitivity of the nozzle design to the propeller functioning and consequently, the necessity of tailored designs. The results of the optimization activities are summarized in the Pareto diagram of Figure 8, where only the Pareto frontier for the three loading conditions are compared and the "optimal" designs for each case (maximized inner pressure at constant nozzle force and, vice versa, maximized nozzle force at constant inner pressure) are highlighted. Also the performance of the reference nozzle geometry operating in correspondence of the three loads are shown. Increasing the propeller load turns into a worsening of the inner pressure at almost constant nozzle drag. In the case of the reference geometry (similarly also for the optimized) the stagnation point moves to the outer surface of the nozzle (Figure 9) in the case of higher loads which imply a stronger contraction of the streamlines and a resulting "negative" angle of attack. Optimization allows certain margins for what regards both the maximization of the inner pressure and the reduction of the nozzle drag. In the worst case of the high propeller load (+20%), ID 2187 allows for positive values of inner pressure reducing the risk of cavitation with respect to the undisturbed flow. Similarly also a reduction of the nozzle drag is possible, regardless the propeller loading. In this case, however, the higher improvements are achieved with the high propeller load and ID 2182 ensures the higher relative improvement in terms of forces (Table 2) with respect to all the others optimal configurations identified with different propeller loadings.

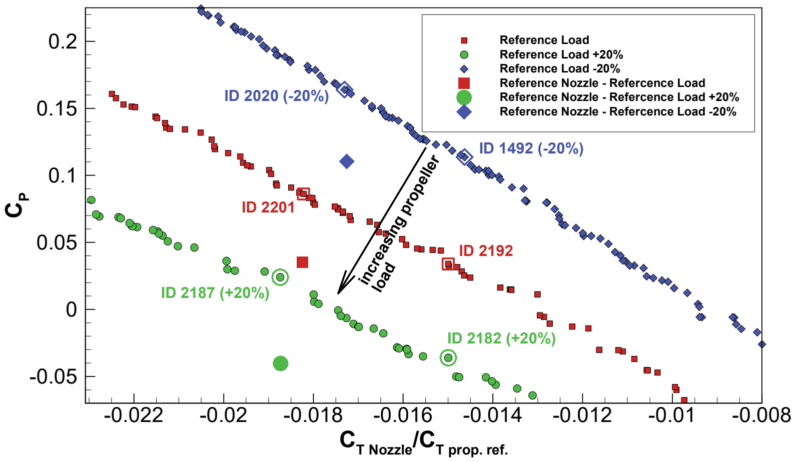
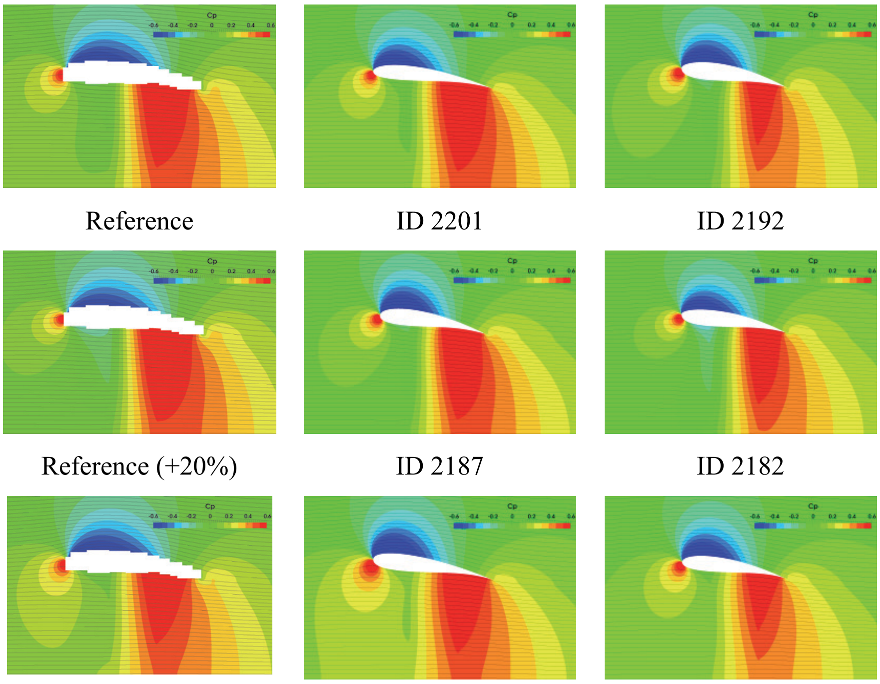


Figure 8: Comparison of the Pareto frontier for different propeller loading distributions.

Table 2: Performance of the selected designs for the decelerating duct case.

	Ref.	Ref. (+20%)	Ref. (-20%)	ID 2201	ID 2192	ID 2187	ID 2182	ID 2020	ID 1492
$C_{T\ Nozzle}$ / $C_{T\ ref.}$	-0.018	-0.0187	-0.0173	-0.0182	-0.0149	-0.0187	-0.0149	-0.0173	-0.0146
C_P	0.035	-0.041	0.111	0.0861	0.0340	0.0239	-0.036	0.164	0.114



Reference ID 2201 ID 2192

Reference (+20%) ID 2187 ID 2182

Reference (-20%) ID 2020 ID 1492

Figure 9: Streamlines and inner pressure distribution for the selected optimal geometries. Decelerating nozzle.

At constant inner pressure, the drag of the nozzle can be reduced up to 20%, which may represent a certain margin for the redesign of a propeller in a more favorable, for cavitation inception, unloaded functioning condition. Independently from the loadings, the optimal shapes are shorter and thinner [5,6], demonstrating the need of appropriate structural constraints for real and feasible applications. The suction peak on the outer duct surface is not sensibly affected by the geometrical modifications and the risk of sheet cavitation on the nozzle, even though not directly monitored throughout the optimization process, is not appreciably enlarged for the selected geometries.

4 CONCLUSIONS

In this paper, an optimization approach for the design of the nozzles for ducted propeller applications has been proposed. The design workflow, consisting in a parametric description of nozzle shape, in a fully scriptable mesh generation tool based on the OpenFOAM *blockMesh* library, in the efficient RANSE solver *simpleFOAM* and in an automatic post-processing of the data together combined through the ModeFrontier optimization environment, was applied for the design of both accelerating and decelerating ducts. The numerical model employed a simplified actuator disk with radially varying momentum sources in order to achieve the necessary computational efficiency required by a design through optimization. Common accelerating nozzles were designed for highly (tip) loaded propellers while for decelerating type shapes the availability of design guidelines is even more scarce, preventing their reliable application to different cases, such tip unloaded blades or lightly loaded conditions. The optimization environment meets these requirements: provide a reliable tool to customize the nozzle shape based on different objectives and constraints, allowing for the fully exploitation of the potentialities of ducted propellers. In the case of the accelerating duct it was possible to identify a set of trade-offs configurations for the multiple functioning conditions simultaneously addressed in the optimization. Improving the cavity inception speed was possible without any detrimental effects on thrust at both bollard pull and at the higher advance coefficient selected to resemble the routinely functioning of the propeller. A first step towards the combined design of the whole propulsive system was proposed in the case of the decelerating nozzle by analyzing designs for three different propeller loading. Also in this case, the outcomes of the design by optimization were encouraging. It was demonstrated that a dedicated nozzle design, as in the previous case, supports simultaneously the increase of the inner pressure and the reduction of drag, showing the benefits of a custom design based on actual requisites.

A redesign of the propeller geometry based on the newly devised nozzle shapes would give an insight into the possibility to improve the overall propulsive performance by using a propeller operating in a more favorable inflow, with a higher static pressure or in correspondence to a different functioning point thanks to the reduction of the nozzle drag. Definitely, a feedback mechanism would be necessary in order to account for the mutual influence between the propeller and the duct and carry out a combined design. The goal, finally, would be the simultaneous design of the nozzle and of the propeller by employing the well-established procedure for propeller optimization including the systematic variation of the duct driven by high-fidelity viscous calculations.

REFERENCES

[1] Sánchez-Caja, A., Pérez-Sobrino, M., Quereda, R., Nijland, M., Veikonheimo, T., González-Adalid, J., Saisto, I. and Uriarte, A., Combination of Pod, CLT and CRP Propulsion for Improving Ship Efficiency: the TRIPOD project. In *Proceedings of Third International Symposium on Marine Propulsors* (2013), Launceston, Australia.

[2] Stipa, L., Experiments with intubed propellers. *L'Aerotecnica* (1932), 923–953.

[3] Kort, L., Der neue dusenschrauben-antrieb, *Werft, Reederei und Hafen* (1934).

[4] Van Manen, J.D., Open Water test series with propellers in nozzles, *International Shipbuilding Progress* (1954) 1(3).

[5] Van Manen, J. D. and Superina, A., The design of screw propellers in nozzles, *International Shipbuilding Progress* (1959), 6(55), 95-113.

[6] Van Manen, J. D. and Oosterveld, M. W. C., Analysis of ducted propeller design, *Trans. SNAME* (1966), 74, 522-561.

[7] Abdel-Maksoud, M., Steden, M. and Hundemer, J., Design of a multi-component propulsors, In *Proceedings of 28th Symposium on Naval Hydrodynamics* (2010), Pasadena, California, USA.

[8] Gaggero, S., Rizzo, C. M., Tani, G. and Viviani, M., EFD and CFD design and analysis of a propeller in decelerating duct, *International Journal of Rotating Machinery* (2012).

[9] Bontempo, R., Cardone, M., and Manna, M., Performance analysis of ducted marine propellers. Part I–Decelerating duct, *Applied Ocean Research* (2016), 58, 322-330.

[10] Hoekstra, M., A RANS-based analysis tool for ducted propeller systems in open water condition, *International shipbuilding progress* (2006), 53(3), 205-227.

[11] Baltazar, J., Rijpkema, D., Falcao de Campos, J. A. C., and Bosschers, J, A comparison of panel method and RANS calculations for a ducted propeller system in open-water, *Proceedings of the Third International Symposium on Marine Propulsors* (2013), Launceston, Australia.

[12] Weller, H. G., Tabor, G., Jasak, H. and Fureby, C. (1998). A tensorial approach to computational continuum mechanics using object-oriented techniques, *Computers in physics* (1998), 12(6), 620-631.

[13] Bosschers, J., Willemsen, C., Peddle, A. and Rijpkema, D., Analysis of Ducted Propellers by Combining Potential Flow and RANS Methods, *Proceedings of the Fourth International Symposium on Marine Propulsors* (2015), Austin, Texas, USA.

[14] Gaggero, S., Gonzalez-Adalid, J., and Sobrino, M. P., Design and analysis of a new generation of CLT propellers, *Applied Ocean Research* (2016), 59, 424-450.

[15] Olivucci, P. and Gaggero, S. (2016). A framework for the design by optimization of hydrofoils under cavitating conditions. *Proceedings of the 7th European Congress on Computational Methods in Applied Sciences and Engineering* (2016), Crete, Greece.

[16] Vernengo, G., Bonfiglio, L., Gaggero, S., and Brizzolara, S., Physics-Based Design by Optimization of Unconventional Supercavitating Hydrofoils, *Journal of Ship Research* (2016), 60(4), 187-202.

[17] Gaggero, S., Villa, D., Tani, G., Viviani, M. and Bertetta, D., Design of ducted propeller nozzles through a RANSE-based optimization approach, *submitted to Ocean Engineering* (2017).

[18] Esteco S.r.l., ModeFRONTIER 2016 User's Manual (2016).